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Relativistic Jets in Radio-Weak Quasars and LINER Galaxies

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Abstract: We discuss radio observations of a sample of radio-weak and radio-intermediate quasars which demonstrate that – just like their radio-loud counterparts – radio-weak quasars too have relativistic jets in their nuclei. Moreover, a VLA survey of nearby LINER galaxies reveals a relatively large number of flat-spectrum radio cores. It is suggested that those cores are also best explained by moderately relativistic jets ($\gamma \sim 2$) produced by a central engine.

1 Introduction

When we discuss the properties of relativistic jets in AGN, we usually tend to think about radio galaxies and radio-loud, core-dominated quasars. The observation of superluminal motion and of many other indicators of high bulk Lorentz factors in these sources have established the existence of relativistic jets there beyond any doubt. But is this the whole universe, or just the tip of the iceberg?

In comparison to stellar winds it is often argued that the escape speed from the central object is an important factor that determines the terminal jet speed. If that is true and since we believe that most of the AGN are powered by a black hole — which in fact may eventually become a definition rather than a conclusion — one should assume that if an AGN produces a jet it should *always* be relativistic. Consequently the crucial question then becomes: Which classes of AGN have jets? In Falcke (1994) and Falcke & Biermann (1995) we wrote down a bold (or should

one say naive?) hypothesis, simply stating that since black holes do not have many free parameters, AGN should be similar in their basic properties ("the universal engine", Falcke 1996a) and hence one should *ab initio* assume that all AGN have relativistic jets rather than only a few sub-classes. As it turned out, this hypothesis, in its simplicity, was surprisingly successful. Here we want to discuss the evidence we have recently gathered for the importance of relativistic jets in other classes of AGN, namely radio-weak quasars and LINER galaxies.

2 Relativistic jets in radio-quiet quasars

If one looks at the distribution of the radio-to-optical flux ratios (R-parameter) of an optically selected quasar sample (here the PG quasar sample) one finds a clear dichotomy between radio-loud and radio-quiet sources. This is especially true if one only selects steep-spectrum quasars, which are supposedly unaffected by orientation effects. VLA observations of the steep-spectrum radio-loud PG quasars (Miller, Rawlings, & Saunders 1993) and Kellerman et al. (1994) have clearly established, that those sources have FR II-type radio jets. This dichotomy was occasionally attributed to the fact that radio-quiet quasars do not show and do not have radio-jets at all. However, as we all know, 'absence of evidence is not evidence of absence' — especially not, if one has not even looked yet.

2.1 Predictions for boosted radio-quiet jets

Let us therefore ask: what would be the consequences, if radio-quiet quasars too would have relativistic jets? As for radio-loud quasars, the most prominent sources would be those which are pointing towards us and are relativistically boosted. In an optically selected sample, we would expect that, if radio-quiet quasars have relativistic jets, some of the quasars are accidentally pointing towards us, thus producing a population of 'weak blazars' with the following properties:

a) similar to flat-spectrum, core-dominated, variable radio quasars but with relative low R-parameter,
b) brightness temperatures close to $\sim 10^{12}$K or above,
c) superluminal motion,
d) very faint (i.e. radio-quiet) extended radio emission,
e) number of sources in a well selected sample, and their Doppler-boosting relative to radio-quiet quasars both imply the same Lorentz factor,
f) luminosity- and z-distribution consistent with radio-quiet parent population,
g) host galaxies compatible with those of radio-quiet quasars.

This list is quite helpful, as it allows an either/or decision: if we do not find a population of weak blazars, we can exclude that relativistic jets in radio-quiet quasars exist (or one would have to invent an argument why those jets never point towards us); if we find them, we can prove that radio-quiet quasars must have relativistic jets. Interestingly, in the PG quasar sample, we indeed find a

population of quasars, which at least partially fulfill most of the criteria listed above and most likely are such weak blazars.

2.2 Radio-intermediate quasars

Miller et al. (1993) and Falcke et al. (1995 & 1996a) identified a small sample of radio-intermediate quasars (RIQ) which sparsely fill the space in R between radio-loud and radio-quiet quasars. They have optical+UV luminosities between 10^{45} and 10^{47} erg/sec, just like the bulk of the radio-quiet quasars, and unlike radio-loud quasars which can be found only above 10^{46} erg/sec in the PG sample. They are typical flat-spectrum, core-dominated quasars, but their R parameter is too low for them to be boosted radio-loud quasars. Their number and R-distribution compared to the radio-quiet quasars would indicate a bulk Lorentz factor of 2-4. For at least the three low-redshift RIQ, there is no extended emission above a level of a few mJy—far below what is expected for any radio-loud quasar—neither on the VLA A- & D-array (Kellerman et al. 1994) nor on the EVN & MERLIN scales (Falcke et al. 1996b). At least one source, III Zw 2, has shown outbursts, indicating a brightness temperature of 10^{12} K (Teräsranta & Valtaoja 1994) which requires relativistic boosting, while VLBI observations of the three low-z sources indicate at least lower limits of several 10^{10} K. Hence, those sources meet all the requirements for intrinsically radio-quiet quasars, whose relativistic jets accidentally point towards us.

2.3 Host galaxies

In the meantime, since the papers have been published, one other prediction has been verified. In Falcke et al. (1996b), we suggested that in order to test the idea of the RIQ being intrinsically radio-quiet, at least half of the flat-spectrum RIQ should have spiral host galaxies. So far, powerful radio galaxies and radio-loud quasars have turned out to reside in elliptical hosts, while radio-quiet quasars seem to reside in a mix of spiral and elliptical galaxies (Kukula et al. 1997). Luckily, two of the three low-redshift RIQ were part of recent host galaxy studies: HST observations of PG 1309+355 (Bahcall et al. 1997) and NIR observations of III Zw 2 (Taylor et al. 1996) have now shown that indeed both galaxies are spirals. This finally confirms, that the RIQ cannot be and never will be radio-loud quasars (as they have been classified occasionally in the past).

2.4 Direct observations of jets

The only piece missing is direct confirmation of relativistic jets in radio-quiet quasars; specifically superluminal motion has not yet been observed. This is, however, not surprising given the observational difficulties for these weak sources. VLBI observations of radio-quiet quasars have just recently begun and even they lack the sensitivity to detect additional components besides the core. Deep, long-integration VLBI observations of radio-quiet quasars are certainly needed. On the

other hand we can at least give a preliminary answer to the question whether direct evidence for jets in radio-quiet quasars exists at all. VLA observations of Kellerman et al. (1994) have already revealed a number of radio-quiet quasars with weak, bi-polar radio-structure. Moreover, there is a certain regime, where the Seyfert and quasar classifications blend into each other. In Fig. 1 we show a VLA map of Mrk 34 (Falcke et al. 1997) which is classified as a Seyfert 2 galaxy, but has an [O III] luminosity which is typical for a radio-quiet PG quasar with an optical+UV luminosity of several 10^{45} erg/sec. The initial snapshot map of this galaxy (Ulvestad & Wilson 1984) also looked like some of the structures Kellerman et al. (1994) found in some PG quasars. The map in Fig. 1 now shows what kind of radio-quiet (!) jets one can get, if one integrates long enough.

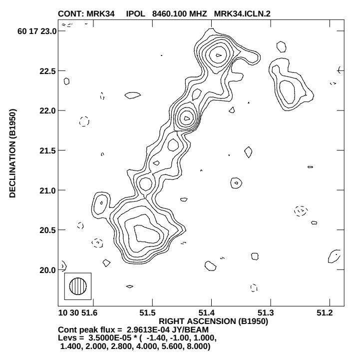

Fig. 1. VLA map at 3.5cm of Mrk 34, a 'Seyfert 2' galaxy with an [O III] luminosity typical for a radio-quiet quasar (from Falcke et al. 1997); the beam is $0.25''$. Only long integration reveals the beautiful jet structure in this galaxy.

3. Relativistic jets in LINER galaxies

Besides radio-quiet quasars, there is another regime where one might be able to find relativistic jets. What happens with those jets in quasars if the accretion rate becomes lower and lower? Will those jets die completely, implying that accretion near the Eddington limit is required for the jet formation, or will the jet just become proportionally weaker, implying that jet formation is an integral part of accretion physics? To learn more about this question one first has to search for and then study jets in low-luminosity AGN. Ho et al. (1995 & 1997) found that roughly one half of nearby galaxies show signs of nuclear activity, in the form of LINER or Seyfert spectra. The bolometric luminosities of these AGN (excluding the host galaxy of course) are in the range $10^{41} - 10^{44}$ erg/sec. Heckman (1980) has speculated that LINER galaxies may preferentially host compact radio cores in their nuclei; these cores could be interpreted as scaled down versions of the compact radio cores and jets in radio-loud quasars (Falcke 1996b&c).

To test this, we have performed a VLA A-array survey at 2cm of 48 nearby LINER galaxies (Falcke, Wilson, & Ho in prep.) from the Ho et al. (1995) sample to

search for compact, flat-spectrum radio nuclei. The 5σ detection limit of the survey was 1 mJy. In total we detected 21 galaxies at this wavelength. Eleven of them have flat spectra, six have steep spectra, and four have, as yet, undetermined spectra. Further VLA observations at 6cm and 3.5cm of these sources are currently being reduced, so that in the near future we expect to have complete spectral information for all galaxies. We note that out of the 11 flat-spectrum sources, 9 are in spiral galaxies.

Our detection rate of flat-spectrum, compact nuclei at 2cm is relatively high and confirms the initial hunch that LINERs would make a good sample to detect compact radio nuclei. For comparison, Vila et al. (1990) looked at a sample of Sbc galaxies with nuclear radio components and only detected 2 flat-spectrum nuclei in a sample of 27 galaxies—both of those galaxies were LINERs. In elliptical galaxies, however, the detection rate of compact nuclei is higher (Wrobel & Heeschen 1991).

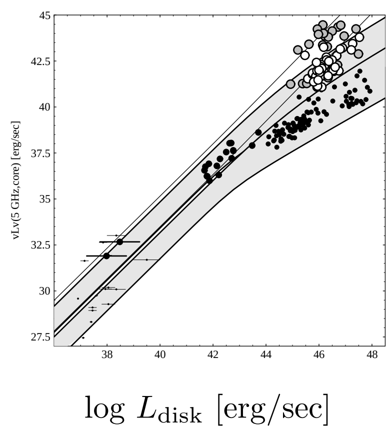

Fig. 2. Correlation between accretion disk luminosity (i.e. nuclear optical+UV luminosity for AGN) and monochromatic radio core luminosity at 5 GHz. The shaded bands are the theoretical predictions as presented in Falcke & Biermann (1996) of radio core luminosities as a function of accretion disk luminosity for relativistic jets with randomly oriented inclination angles. The radio cores of the newly added LINER galaxies are given by big dots, quasars are given by open (steep-spectrum, radio-loud) and filled circles (flat-spectrum, radio-loud), and smaller dots (radio-quiet) above $L_{\rm disk} = 10^{44}$ erg/sec. Sources in the lower left are Sgr A*, M31* and stellar mass black holes (see Falcke & Biermann for more details).

Of course, the mere fact that we find these radio nuclei in LINERs does not prove yet that those radio cores are indeed related to the active nucleus or that they are jets. We therefore looked at the relation between radio and optical Hα flux in those galaxies and found a good correlation. This is in line with earlier claims of a connection between optical and radio activity (Ekers & Ekers 1973, O'Connell & Dressel 1978).

Hence, we conclude that the radio cores in LINERs are indeed part of the central engine. Moreover, we can compare the radio and emission-line luminosities with the jet/disk model by Falcke & Biermann (1996), to learn more about their nature. The model predicted a specific radio/nuclear luminosity correlation for

low-power AGN and is based on the assumption that accretion disk luminosity and jet power in AGN are coupled by a universal constant. We note that this may remain true even for advection dominated disks, as have been discussed for LINERs (Lasota et al. 1996), if the radiative efficieny of the radio and the optical emission in a jet/disk system are reduced in the same way (i.e. the jet power is proportional to the energy dissipated in the disk rather than to the accretion rate).

For a randomly selected (and randomly oriented) sample, the width ('scatter') of the radio-to-nuclear UV distribution is given by the typical Lorentz factor of the jets. In Fig. 2 we reproduce (without changing any parameters) the figure from Falcke & Biermann, where the model prediction for low-power AGN was given as shaded bands for a jet Lorentz factor of ~ 2. We then converted the *narrow* Hα line-luminosities of the LINERs with detected flat-spectrum nuclei to optical+UV luminosities, using the same proportionality factors as for the quasars[1], and inserted them into the correlation (big dots). Obviously the LINERs fall exactly into the range predicted for low-luminosity, *radio-loud* jets. This confirms a preliminary version of this diagram which was presented in Falcke (1996c), but was based only on a few ill-selected, famous LINER galaxies.

This result not only strongly suggests that LINERs do have powerful nuclear radio jets — for some individual cases this is know already (e.g. M87; NGC4258, Herrnstein et al. 1997; M81, Bietenholz et al. 1996, etc.) — but is also consistent with mildly relativistic Lorentz factors around $\gamma_{\rm j} \simeq 2$ as used in the model. That should be compared with Lorentz factors of $\gamma \simeq 6 - 10$ derived with the same method for radio-loud quasars (Falcke et al. 1995). For the lower Lorentz factor in LINERs (and also in the Galactic superluminal sources) one can give a very simple explanation, since this terminal velocity is naturally obtained by a relativistic plasma in a simple pressure driven jet (Falcke 1996b). To explain the velocities in radio-loud and radio-quiet quasars, however, one needs an extra mechanism that provides the additional push necessary to go beyond $\gamma_{\rm j} = 3$.

4 Conclusions

Based on the experience gathered on relativistic jets in quasars and radio galaxies, one can make a number of specific predictions for signs of relativistic jets in other samples of AGN. Especially for radio-weak quasars a number of those predictions has been verified for a sample as well as for individual cases, making it very likely that relativistic jets do in fact exist in many, if not all, radio-quiet quasars. A search for similar jets in low-power galaxies has just begun, but there is already data suggestive of the existence of relativistic jets in LINERs. The study of those sources will greatly expand our horizon and may eventually help us to understand the underlying principle governing the formation of jets in general.

[1] See Falcke et al. 1995 & Falcke 1996a. The exact conversion factors for LINERs require of course a more thorough discussion. For a few examples (e.g. M81, NGC 4252) this method at least seems to give a reasonable estimate for the nuclear luminosity

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